

# $\text{N}_2\text{H}^+$ and $\text{HC}_3\text{N}$ Observations of the Orion A Cloud

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## Abstract

The “ $f$ -shaped filament” of the Orion A giant molecular cloud was mapped in  $\text{N}_2\text{H}^+$   $J = 1 \rightarrow 0$ , and its northern end, the OMC-2/3 region was observed also in  $\text{HC}_3\text{N}$   $J = 5 \rightarrow 4$  and CCS  $J_N = 4_3 \rightarrow 3_2$  and  $7_6 \rightarrow 6_5$ . The results are compared with maps of other molecular lines and the dust continuum emission. The  $\text{N}_2\text{H}^+$  distribution is similar to the dust continuum distribution, except for the central part of the Orion Nebula. The distribution of  $\text{H}^{13}\text{CO}^+$  holds resemblance to that of dust continuum, but the  $\text{N}_2\text{H}^+$  distribution looks more similar to dust continuum distribution. The N-bearing molecules,  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  seem to be more intense in OMC-2, compared with the  $\text{H}^{13}\text{CO}^+$  and CS distribution. This suggests that OMC-2 has higher abundance of N-bearing molecules or higher filling factor of the quiescent gas. We identified 34 cloud cores from  $\text{N}_2\text{H}^+$  data. Their average physical parameters are  $T_{\text{ex}} = 9.2 \pm 4.2$  K,  $\Delta v = 0.92 \pm 0.52$  km s $^{-1}$ ,  $R = 0.086 \pm 0.025$  pc, and  $M = 46 \pm 32 M_\odot$ . The masses of cores identified in both  $\text{N}_2\text{H}^+$  and  $\text{H}^{13}\text{CO}^+$  in the OMC-2/3 region are rather consistent. Over the Orion Nebula region, the  $\text{N}_2\text{H}^+$  linewidth is large (1.1–2.1 km s $^{-1}$ ). In the OMC-2/3 region, it becomes moderate (0.5–1.3 km s $^{-1}$ ), and it is smaller (0.3–1.1 km s $^{-1}$ ) in the south of the Orion Nebula. On the other hand, the gas kinetic temperature of the quiescent cores observed in  $\text{N}_2\text{H}^+$  is rather constant ( $\sim 20$  K) over the  $f$ -shaped filament. The average  $\text{N}_2\text{H}^+$  excitation temperature in Orion cores is  $\sim 1.6$  times as high as that in Taurus cores ( $\sim 5.7$  K). The  $\text{N}_2\text{H}^+$  excitation temperature decreases toward the south, suggesting the core gas density or  $\text{N}_2\text{H}^+$  abundance decreases toward the south. We found one peculiar  $\text{H}^{13}\text{CO}^+$  core which is not prominent in either  $\text{N}_2\text{H}^+$ ,  $\text{HC}_3\text{N}$ , or dust. This core overlaps with the lobe of the intense outflow from a nearby protostar. We detected no CCS emission in the OMC-2/3 region. In general,  $\text{N}_2\text{H}^+$  and  $\text{HC}_3\text{N}$  distribution is quite similar in the OMC-2/3 region, but we observed displacement between  $\text{N}_2\text{H}^+$  and  $\text{HC}_3\text{N}$  over  $2'$  scale in OMC-3, which has a chain of Class 0-I protostars (candidates). This displacement might be due to either chemical evolution or effect of protostellar outflows.

**Key words:** ISM: clouds —ISM: individual (Orion Nebula, Orion Molecular Cloud) —ISM: molecules —ISM: structure—stars: formation

## 1. Introduction

Most of stars in the Galaxy form in giant molecular clouds. The molecular cloud core is known to be the site of star formation (e.g., Beichman et al. (1986)). The evolution of molecular cloud cores in giant molecular clouds is less known, compared with that of low-mass dark cloud cores. In dark clouds, molecules such as CCS, HC<sub>3</sub>N, NH<sub>3</sub>, and N<sub>2</sub>H<sup>+</sup>, and the neutral carbon atom C<sup>0</sup> are known to be good tracer of chemical evolution (e.g., Hirahara et al. 1992; Suzuki et al. 1992; Maezawa et al. 1999; Hirota et al. 2002). The carbon chain molecules, CCS and HC<sub>3</sub>N tend to trace the early chemical evolutionary stage, whereas NH<sub>3</sub> and N<sub>2</sub>H<sup>+</sup> tend to trace the later stage. It is now well known that N<sub>2</sub>H<sup>+</sup>, which is less affected by depletion, is one of the best molecular tracers for low-mass star forming regions (e.g., Caselli et al. 1999; Aikawa et al. 2001; Bergin et al. 2001; Bergin et al. 2002; Caselli et al. 2002b; Li et al. 2002; Tafalla et al. 2002; Lee et al. 2003; Shematovich et al. 2003).

The Orion A cloud is an archetypal giant molecular cloud. This cloud has been extensively mapped in <sup>12</sup>CO  $J = 1 \rightarrow 0$  (Heyer et al. 1992), in <sup>13</sup>CO  $J = 1 \rightarrow 0$  (Bally et al. 1987; Nagahama et al. 1998), in CS  $J = 1 \rightarrow 0$  (Tatematsu et al. 1993), in CS  $J = 2 \rightarrow 1$  (Tatematsu et al. 1998), in NH<sub>3</sub> (Batra et al. 1983; Cesaroni & Wilson 1994), and in H<sup>13</sup>CO<sup>+</sup>  $J = 1 \rightarrow 0$  (Ikeda et al. 2007). The dust continuum emission in the Orion A cloud was studied by Chini et al. (1997), Lis et al. (1998), and Johnstone & Bally (1999). The region near Orion KL was studied in many molecular lines by Ungerechts et al. (1997).

Of particular interest is the OMC-2/3 region, which is the northernmost part of the Orion A cloud. This region is one of the best studied intermediate-mass star forming regions. Chini et al. (1997) investigated the distribution of the dust continuum emission and found at least 21 protostellar dust condensations. Aso et al. (2000) observed H<sup>13</sup>CO<sup>+</sup> and CO in this region, and identified cloud cores and outflows. Outflows were also observed by Yu et al. (2000); Williams et al. (2003). Takahashi et al. (2006) studied a molecular cloud core and an outflow associated with the protostar MMS7 in detail. Tsujimoto et al. (2002); Tsujimoto et al. (2003) investigated the properties of the X-ray sources observed with the Chandra Observatory, and identified/classified them on the basis of near infrared observations (Class I, Class II, and Class III+MS, brown dwarf candidates). Tsuboi et al. (2001) detected the X-ray emission from two protostar candidates in OMC-3. Tsujimoto et al. (2004) concluded that one of these two X-ray sources is the shock-induced X-ray emission by protostellar jet from Class I protostar(s). Johnstone et al. (2003) observed seven submillimeter sources in eight molecular lines and investigated the physical condition.

In this study, we revisit the Orion A cloud, including the OMC-2/3 region, through new

molecular-line observations. The purposes of this study are (1) to make clear the distribution of the quiescent molecular gas and to compare it with star formation activity, (2) to describe the chemical evolution in the OMC-2/3 region, (3) to compare the physical properties of  $\text{N}_2\text{H}^+$  cores in the Orion massive star-forming region with those in the low-mass star forming dark cloud found in Taurus, and (4) to investigate variation in  $\text{N}_2\text{H}^+$  core properties along the “ $f$ -shaped filament.”

The distance to the Orion A cloud is assumed to be 450 pc (Genzel & Stutzki 1989). At this distance,  $1'$  corresponds to 0.13 pc.

## 2. Observations

Observations were carried out by using the 45 m radio telescope of Nobeyama Radio Observatory from 2005 May 11 to 20, and from 2007 March 4 to 9. The employed receiver front ends were the 25-element focal-plane SIS array receiver “BEARS”, and the single-element SIS receivers, “S100” and “S40”. We observed  $\text{N}_2\text{H}^+$   $J = 1 \rightarrow 0$  at 93.1737767 GHz (Caselli et al. 1995) by using receiver “BEARS”, CCS  $J_N = 4_3-3_2$  at 45.379033 GHz (Yamamoto et al. 1990) by using receiver “S40”, CCS  $J_N = 7_6-6_5$  at 81.505208 GHz (Hirota & Yamamoto 2006) by using receiver “S100”, and  $\text{HC}_3\text{N}$   $J = 5-4$  at 45.490316 GHz (Yamamoto et al. 1990) by using receiver “S40”. CCS and  $\text{HC}_3\text{N}$  were observed simultaneously, by using two receivers with the polarization splitter. The half-power beamwidth of the element beam of BEARS was  $17''.8 \pm 0''.4$  at 93 GHz. Those of S40 and S100 are  $38''.4 \pm 0''.1$  and  $18''.2 \pm 0''.1$  at 43 and 86 GHz, respectively. The beam separation of “BEARS” is  $41''.1$ . The spacing grid employed in mapping observations with “BEARS” was  $20''.55$ , which is half of the beam separation of elements within the array and close to the half-power beamwidth. The spacing grid employed in “S40” and “S100” observations was  $40''$ . The receiver back end for “BEARS” was a digital autocorrelator and that for “S40” and “S100” was acousto-optical spectrometers. The spectral resolution for “BEARS” was 37.8 kHz (corresponding to  $\sim 0.12 \text{ km s}^{-1}$  at 93 GHz) and that for “S40” and “S100” was 37 kHz (corresponding to  $\sim 0.25 \text{ km s}^{-1}$  at 45 GHz and  $0.14 \text{ km s}^{-1}$  at 81 GHz). The map reference center is Orion KL at R. A. (J2000) =  $5^h 35^m 14^s.5$ , Dec. (J2000) =  $-5^\circ 22' 30''$ . Spectra were obtained in the position-switching mode. The employed off position is either  $(\Delta \text{ R. A.}, \Delta \text{ Dec.}) = (-30', 5')$  or  $(0', -100')$  with respect to Orion KL. We calibrated the gain of each “BEARS” element and obtained the absolute intensity scale in the way described in Tatematsu et al. (2004). The intensity is reported in terms of the corrected antenna temperature  $T_A^*$ . The main-beam efficiency is  $0.77 \pm 0.03$  for “S40”, and  $0.51 \pm 0.02$  for “S100” and “BEARS”. The telescope pointing was established by observing Orion KL in the 43-GHz SiO maser line every 1–1.5 hours. The data were reduced by using the software package NewStar of Nobeyama Radio Observatory and IDL of Research Systems, Inc.

## 3. Results and Discussion

### 3.1. $\text{N}_2\text{H}^+$ Observation

Figures 1 and 2 show the distribution of the velocity-integrated intensity of the  $\text{N}_2\text{H}^+$   $J = 1 \rightarrow 0$   $F_1 = 2 \rightarrow 1$  hyperfine group. Because the linewidth is broad, we cannot separate hyperfine components well. Therefore, we integrated the three components including the most intense main component. The total length of the filament is about 12 pc, and the figures exhibit filamentary and clumpy structure well.

Figures 3 and 4 show a comparison of  $\text{N}_2\text{H}^+$   $J = 1 \rightarrow 0$   $F_1 = 2 \rightarrow 1$  hyperfine group map with  $850 \mu\text{m}$  thermal dust continuum emission map (Johnstone & Bally 1999) in a closer

**Fig. 1.** The grey-scale map of the velocity-integrated intensity of the  $\text{N}_2\text{H}^+$   $J=1 \rightarrow 0$   $F_1 = 2 \rightarrow 1$  hyperfine group. The level interval for the contour is  $0.749 \text{ K km s}^{-1}$ . Pluses represent Orion KL (labeled as “Orion KL”) and cores identified in  $\text{N}_2\text{H}^+$ .

**Fig. 2.** The contour map of the velocity-integrated intensity of the  $\text{N}_2\text{H}^+$   $J=1 \rightarrow 0$   $F_1 = 2 \rightarrow 1$  hyperfine group. The contour levels are  $0.749 \text{ K km s}^{-1} \times (1, 2, 4, 8)$ . The intensity maxima of the  $\text{N}_2\text{H}^+$  cores are shown as pluses.

view of Orion KL. These maps show that the  $\text{N}_2\text{H}^+$  distribution resembles the dust continuum distribution very well. For example, V-shaped structure about  $15'$  south of Orion KL is very clear in both maps. However, it should be noted that the Orion bar, which is prominent in the dust continuum, is not seen in  $\text{N}_2\text{H}^+$ .  $\text{N}_2\text{H}^+$  is known to be sensitive to quiescent molecular gas, while the dust continuum is sensitive to the photodissociation region (PDR). The dust distribution is thinner in width and more compact than the  $\text{N}_2\text{H}^+$  distribution, because structures with scales larger than the largest chopper throw ( $65''$ ) are missing from the dust continuum map.

We identified  $\text{N}_2\text{H}^+$  cores by using two sets of the velocity channel maps. The first set is  $0.3 \text{ km s}^{-1}$ -width velocity channel maps of the  $F_1$ ,  $F = 0, 1 \rightarrow 1, 2$  component, which is an isolated component of the seven hyperfine components. The advantage of this set is that we can separate molecular gas having different velocities easily. However, in some cases the signal-to-noise ratio is not sufficient. The second set is  $0.5 \text{ km s}^{-1}$ -width velocity channel maps of  $F_1 = 2 \rightarrow 1$  hyperfine group, which contains the most intense hyperfine component  $F_1, F = 2, 3 \rightarrow 1, 2$  and two neighboring hyperfine components. This hyperfine group has three components in the velocity range of less than  $2 \text{ km s}^{-1}$ , and it is hard to derive detailed velocity structure. On the other hand, we can detect molecular gas having weaker intensities with this set. By taking advantages of these two sets, we have identified a total of 34 molecular cloud cores in  $\text{N}_2\text{H}^+$ . Table 1 summarizes the identification by eye and properties of  $\text{N}_2\text{H}^+$  cores. The value after  $\pm$  in the antenna temperature, excitation temperature, optical depth, and linewidth shows the  $1\sigma$  uncertainty in the hyperfine fitting to the spectrum toward the intensity maximum. The bottom row with “ave” lists the average and standard deviation for all cores.

The positions of the intensity maxima of the identified cores are illustrated in Figures 1, 2, and 3. Orion KL is not prominent in  $\text{N}_2\text{H}^+$ , and is not cataloged as a core. It is located on the eastern bay of the  $\text{N}_2\text{H}^+$  emission ridge. The basic physical parameters of the identified cores

**Fig. 3.** The velocity-integrated map of the  $\text{N}_2\text{H}^+$   $J=1 \rightarrow 0$   $F_1 = 2 \rightarrow 1$  hyperfine group in a closer view of Orion KL. The level interval for the contour is  $0.749 \text{ K km s}^{-1}$ . Pluses represent Orion KL (labeled as “Orion KL”) and cores identified in  $\text{N}_2\text{H}^+$ .

**Fig. 4.** The 850  $\mu\text{m}$  thermal dust continuum emission map (Johnstone & Bally 1999). This map covers the same Dec. range of Figure 2. The image is convolved for the angular resolution of the  $\text{N}_2\text{H}^+$  observation. The level interval for the contour is 0.84 Jy/beam. Pluses represent cores identified in  $\text{N}_2\text{H}^+$ .

**Fig. 5.** The  $\text{N}_2\text{H}^+$  spectrum toward the intensity maximum position of  $\text{N}_2\text{H}^+$  core 4. The best-fit hyperfine fitting result is shown as a smooth curve. The velocity axis is for the main  $\text{N}_2\text{H}^+$   $J = 1 \rightarrow 0$  component ( $F_1, F = 2, 3 \rightarrow 1, 2$ ).

are summarized in Tables 1 and 2. The HWHM (half of FWHM) core radius  $R$  is measured as  $\sqrt{S}/\pi$  ( $S$  is the core area  $S$  at the half maximum), and then corrected for the telescope beam size. We fit the spectrum observed toward the intensity maximum by using the hyperfine spectrum model consisting of multiple Gaussian components including the effects of optical depth assuming a single excitation temperature. Figures 5, 6, 7, 8, and 9 show the examples of the hyperfine fitting. The procedure is given in Tatematsu et al. (2004). The intrinsic relative intensities of the hyperfine components are taken from Tiné et al. (2000). The free parameters are the excitation temperature  $T_{ex}$ , the sum of optical depths of the hyperfine components  $\tau_{TOT}$ , systemic velocity (radial velocity), and intrinsic linewidth (which is corrected for broadening due to line optical depth and instrumental resolution).  $T_A^*$  in the table represents the intensity of the main  $\text{N}_2\text{H}^+$   $J = 1 \rightarrow 0$  component ( $F_1, F = 2, 3 \rightarrow 1, 2$ ) derived in the hyperfine fitting. When the fitting is not very successful, we show approximate  $T_A^*$  values by indicating with “ $\sim$ ”.  $\tau_{TOT}$  represents the total optical depth summing up those of the seven hyperfine components of the  $\text{N}_2\text{H}^+$  emission. The optical depth of the main  $\text{N}_2\text{H}^+$   $J = 1 \rightarrow 0$  component ( $F_1, F = 2, 3 \rightarrow 1, 2$ ) is  $0.259 \times \tau_{TOT}$  (Tiné et al. 2000). The details of the column density estimation are given in Caselli et al. (2002c). The  $\text{H}_2$  column density  $N(\text{H}_2)$  is derived by assuming the  $\text{N}_2\text{H}^+$  fractional abundance relative to  $\text{H}_2$  is  $3.0 \times 10^{-10}$  (Caselli et al. 2002a). The average density  $n(\text{H}_2)$  is derived as  $N(\text{H}_2)/2R$ . For the OMC-2/3 region, we include the existence of molecular outflows and near-infrared  $\text{H}_2$  jets (Aso et al. 2000 and references therein) as “O” and “H”, respectively, in Table 2.

The  $\text{N}_2\text{H}^+$  excitation temperature toward the core intensity peak is  $T_{ex} = 9.2 \pm 4.2$  K (average and standard deviation). This value is 1.6 times as high as that in Taurus cores ( $T_{ex} = 5.7 \pm 1.2$  K for the central nine positions of each core in the Taurus cloud, which is good for comparison with Orion cores by taking into account that Orion is three times more distant, Tatematsu et al. 2004). The optical depth of the main component ( $F_1, F = 2, 3 \rightarrow 1, 2$ ) is found to be moderate ( $1.1 \pm 0.7$ ) for the intensity peak, and this is similar to the situation in Taurus cores (Tatematsu et al. 2004).

**Fig. 6.** The same as Figure 5 but for  $\text{N}_2\text{H}^+$  core 6

**Fig. 7.** The same as Figure 5 but for  $\text{N}_2\text{H}^+$  core 23

**Fig. 8.** The same as Figure 5 but for  $\text{N}_2\text{H}^+$  core 27

We summarize the average physical parameters of  $\text{N}_2\text{H}^+$  cores with standard deviations. The line width is  $\Delta v = 0.92 \pm 0.52 \text{ km s}^{-1}$ , core size is  $R = 0.086 \pm 0.025 \text{ pc}$ , column density is  $N(\text{H}_2) = (6.7 \pm 2.6) \times 10^{22} \text{ cm}^{-2}$ , average density is  $n(\text{H}_2) = (1.2 \pm 0.4) \times 10^5 \text{ cm}^{-3}$ , and core mass is  $M = 46 \pm 32 M_\odot$ . We derived the virial parameter, which is defined as the virial mass divided by the core mass, to be  $0.39 \pm 0.32$ . One possibility is that the actual  $\text{N}_2\text{H}^+$  abundance is higher than the value we assumed. However, the mass estimation usually accompanies uncertainty by a factor of 2-3. Furthermore, it seems that the  $\text{N}_2\text{H}^+$  abundance varies over the  $f$ -shaped filament (see discussion later). Therefore, it would be hard to derive a precise value of  $\text{N}_2\text{H}^+$  abundance on the basis of simple analysis assuming virial equilibrium.

When we compare Orion  $\text{N}_2\text{H}^+$  cores with Taurus  $\text{N}_2\text{H}^+$  cores (Tatematsu et al. 2004), Orion cores have 2.6, 3.2, 4.0 and 32 times larger core size, linewidth,  $\text{H}_2$  column density, and core mass than Taurus cores, respectively. The  $\text{H}_2$  column density in Taurus used here is an average for central nine positions taking into account the difference in distance.

Figures 10 and 11 show a comparison between  $\text{N}_2\text{H}^+$  (present study) and  $\text{H}^{13}\text{CO}^+$  (Aso et al. 2000) in a closer view of the OMC-2/3 region. Basically, the distribution of these tracers is similar. Close inspection lets us see some differences. First, the  $\text{H}^{13}\text{CO}^+$  core AC9 is not prominent in  $\text{N}_2\text{H}^+$ . Second,  $\text{N}_2\text{H}^+$  core 4 does not have a tail toward the south, which is seen in the  $\text{H}^{13}\text{CO}^+$  and in the dust continuum (Figure 4). Third,  $\text{N}_2\text{H}^+$  cores 10 and 12 are more prominent in  $\text{N}_2\text{H}^+$  than  $\text{H}^{13}\text{CO}^+$  counterparts.

Next, we investigate the variation of the core properties along the “ $f$ -shaped filament.” Figure 12 plots the  $\text{N}_2\text{H}^+$  linewidth against the declination. By using the intrinsic  $\text{N}_2\text{H}^+$  linewidth, we investigate the velocity dispersion of the quiescent gas along the “ $f$ -shaped filament.” Over the Orion Nebula region, the linewidth is large ( $1.1\text{--}2.1 \text{ km s}^{-1}$ ). In the OMC-2/3 region, it becomes moderate ( $0.5\text{--}1.3 \text{ km s}^{-1}$ ), and it is smaller ( $0.3\text{--}1.1 \text{ km s}^{-1}$ ) in the south of the Orion Nebula. It is important that we observe the tendency in  $\text{N}_2\text{H}^+$ , which is the molecule least affected from star formation activities such as outflows (Womack et al. 1993). It was suggested that larger linewidths of the quiescent gas to form stars will lead to higher mass accretion rate onto protostars and eventually to more massive stars (see, e.g., Tatematsu et al. 1993). An argument against this idea is that larger linewidths might be a result of more massive star formation. The present study shows a trend in linewidth of the quiescent gas, and

**Fig. 9.** The same as Figure 5 but for  $\text{N}_2\text{H}^+$  core 32



**Fig. 10.** The velocity-integrated map of the  $\text{N}_2\text{H}^+$   $J = 1 \rightarrow 0$   $F_1 = 2 \rightarrow 1$  hyperfine group in a closer view of the OMC-2/3 region. The level interval for the contour is  $0.749 \text{ K km s}^{-1}$ . Pluses represent cores identified in  $\text{N}_2\text{H}^+$ . Thin straight lines represent the border between OMC-2 and OMC-3 used by Chini et al. (1997)

**Fig. 11.** Reproduction of  $\text{H}^{13}\text{CO}^+$  map of Aso et al. (2000), but in J2000 coordinates. This map covers the same R. A. and Dec. range of Figure 10. Contour intervals are  $0.36 \text{ K km s}^{-1}$  starting at  $0.36 \text{ K km s}^{-1}$ . The stars mark the 1.3 mm continuum sources (Chini et al. 1997), and the triangles mark the 350 km continuum sources (Lis et al. 1998).

might suggest that variation in linewidth could serve as difference in the initial condition for on-going star formation in the Orion cloud. The core radius does not show any prominent trend against the declination (figure not shown). Figure 13 shows the temperature variation along the “ $f$ -shaped filament.” The kinetic temperature from CO  $J = 3 \rightarrow 2$  seems to trace the outer, warmer, less-dense layer of the cloud externally heated (Wilson et al. 1999; see also Castets et al. (1990)). The  $\text{NH}_3$  rotation temperature is about 20 K over the filament, implying that the gas temperature of the quiescent dense gas is rather constant. The average and standard deviation of the  $\text{NH}_3$  rotation temperature are 21.6 and 5.3 K, respectively. A rotation temperature of  $\sim 20 \text{ K}$  corresponds to a gas kinetic temperature of  $\sim 20 \text{ K}$  (Danby et al. 1988). Figure 3 of Wilson et al. (1999) shows a clear variation in rotation temperature. However, at positions coincident with quiescent cloud cores identified in  $\text{N}_2\text{H}^+$  and CS, this variation is not seen. It is very interesting that the quiescent Orion cores show constant kinetic temperatures while their linewidth varies along the filament. The kinetic temperature in quiescent Orion cores are twice as high as that in dark cloud cores (8-10 K, see, e.g., Benson & Myers (1980); Tatematsu et al. (1999)) The  $\text{N}_2\text{H}^+$  excitation temperature decreases toward the south slightly, which means that the core density or  $\text{N}_2\text{H}^+$  abundance decreases toward the south. Tatematsu et al. (1993) and Tatematsu et al. (1998) suggested that the Orion A cloud has the average density decrease toward the south. In detail, the excitation temperature seems to have its peak around OMC-2.

$\text{H}^{13}\text{CO}^+$  in the Orion A cloud was observed by Aso et al. (2000) and Ikeda et al. (2007). The distribution in these maps is consistent in the OMC-2/3 region, which was covered by both studies. Ikeda et al. (2007) used automated software to identify cores, while Aso et al. (2000) identified cores through visual inspection. The former identified two times as many cores as Aso et al. (2000) in the OMC-2/3 region. Part of this difference might be due to different sensitivities, but we suspect that different core identification methods are the main

**Fig. 12.** The  $\text{N}_2\text{H}^+$  linewidth against the declination. Labels “OMC-2” and “OMC-3” represent the positions of  $\text{N}_2\text{H}^+$  cores 4 and 10, respectively.



**Fig. 13.** The temperature against the declination. The gas kinetic temperature from CO  $J = 3 \rightarrow 2$  and  $\text{NH}_3$  rotation temperature (Wilson et al. 1999) of cores identified in both CS and  $\text{N}_2\text{H}^+$ , and  $\text{N}_2\text{H}^+$  excitation temperature (present study) of  $\text{N}_2\text{H}^+$  cores are shown. The solid horizontal line represents 20 K.

**Fig. 14.** The  $\text{N}_2\text{H}^+$  linewidth and  $\text{H}^{13}\text{CO}^+$  linewidth in the OMC-2/3 region. Starless cores and star-forming cores are based on classification in Aso et al. (2000).

reason for disparate core numbers. For comparison, we use Aso et al. (2000), which identified cores through visual inspection, for consistency. The cross identification is given in Table 2. The column “Aso” lists  $\text{H}^{13}\text{CO}^+$  cores in Aso et al. (2000), and column “Paper I” lists CS  $J = 1 \rightarrow 0$  cores in Tatematsu et al. (1993).

Using the cores identified in both  $\text{N}_2\text{H}^+$  and  $\text{H}^{13}\text{CO}^+$ , we compare the  $\text{N}_2\text{H}^+$  and  $\text{H}^{13}\text{CO}^+$  cores in the OMC-2/3 region (Figures 14, 15, and 16). The  $\text{N}_2\text{H}^+$  linewidth tends to narrower than the  $\text{H}^{13}\text{CO}^+$  linewidth, which is consistent with the fact that  $\text{N}_2\text{H}^+$  traces the quiescent molecular gas. The core radius and core mass are rather consistent between these two lines, and it is likely that these two molecular lines trace similar density regions, although the linewidth is different to some extent. On the other hand, only eight cores out of 14  $\text{N}_2\text{H}^+$  (cores 1 through 14) in the OMC-2/3 region have  $\text{H}^{13}\text{CO}^+$  counterparts.

$\text{N}_2\text{H}^+$  cores 10 and 12 are more prominent in  $\text{N}_2\text{H}^+$  than  $\text{H}^{13}\text{CO}^+$  counterparts in OMC-2. Tatematsu et al. 1993 showed that, in a region containing Orion KL and OMC-2 (see their Figure 4),  $\text{NH}_3$  tends to be stronger in the north (OMC-2) while CS tends to be stronger in the south. Ungerechts et al. (1997) studied molecular distribution around Orion KL (from  $6'$  south to  $6'$  north), and found that  $\text{N}_2\text{H}^+$  tends to be stronger in the north,  $\text{H}^{13}\text{CO}^+$  shows similar trend but less prominent, and other molecules show different trends (peaked around Orion KL or flat). Figure 17 shows the antenna temperature of  $\text{N}_2\text{H}^+$  cores (present study) and  $\text{H}^{13}\text{CO}^+$  cores (Ikeda et al. 2007) against the declination. The dashed and solid lines delineate the rough upper boundary of the antenna temperature of  $\text{N}_2\text{H}^+$  and  $\text{H}^{13}\text{CO}^+$ , respectively, by connecting local maxima to guide the reader’s eye for the global trend.  $\text{N}_2\text{H}^+$  is intense in OMC-2 ( $\text{N}_2\text{H}^+$  cores 10 and 12) with respect to the  $\text{H}^{13}\text{CO}^+$  intensity variation. Figure 18 shows the antenna temperature of  $\text{N}_2\text{H}^+$  cores (present study) and CS cores (Tatematsu et al. 1993) against the declination. Again,  $\text{N}_2\text{H}^+$  is relatively intense in OMC-2 ( $\text{N}_2\text{H}^+$  cores 10 and 12) with respect to the CS intensity variation. The N-bearing molecules,  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  seem to be more intense in OMC-2 ( $\text{N}_2\text{H}^+$  cores 10 and 12), compared with the  $\text{H}^{13}\text{CO}^+$  and CS distribution. The gas kinetic temperature of quiescent cores is rather constant judging from

**Fig. 15.** The  $\text{N}_2\text{H}^+$  core radius and  $\text{H}^{13}\text{CO}^+$  core radius in the OMC-2/3 region

**Fig. 16.** The  $\text{N}_2\text{H}^+$  core mass and  $\text{H}^{13}\text{CO}^+$  core mass in the OMC-2/3 region

**Fig. 17.** The antenna temperatures of  $\text{N}_2\text{H}^+$  (present study) and  $\text{H}^{13}\text{CO}^+$  (Ikeda et al. 2007) against the declination. The dashed and solid lines connect local maximum intensities in  $\text{N}_2\text{H}^+$  and  $\text{H}^{13}\text{CO}^+$ , respectively, to guide the reader’s eye for the global trend.

the  $\text{NH}_3$  rotation temperature. This suggests that OMC-2 has higher abundance of N-bearing molecules or higher filling factor of the quiescent gas. Although OMC-2 is known as active star cluster forming region (Johnson et al. 1990), it seems that it still has a large reservoir of quiescent gas available for future star formation. Note that N-bearing molecules,  $\text{N}_2\text{H}^+$  and  $\text{NH}_3$  are late-type molecules. Chini et al. (1997) showed that OMC-3 has Class 0 protostars (candidates) and suggested evolutionary trend from north (OMC-3, younger) to south (OMC-2, older). This trend is consistent with the trend in the chemical properties (N-bearing late-type molecules are more abundant in OMC-2).

### 3.2. $\text{HC}_3\text{N}$ and $\text{CCS}$ Observations

Figure 19 compares the  $\text{N}_2\text{H}^+$  with  $\text{HC}_3\text{N}$  distribution in the OMC-2/3. Globally, their distribution is quite similar, although they are known to be late-type and early-type molecules in dark cloud chemistry, respectively (Hirahara et al. 1992). Both are intense in OMC-2. This is in contrast with the fact that OMC-2 is not very prominent compared with OMC-3 in  $\text{H}^{13}\text{CO}^+$ . OMC-2 is known as a cluster forming region (Johnson et al. 1990). Although  $\text{HC}_3\text{N}$  is known to be a tracer of early chemical evolutionary stage in dark clouds (Hirahara et al. 1992), it is not always so. Ungerechts et al. (1997) shows that the  $\text{HC}_3\text{N}$   $J = 10 \rightarrow 9$  and  $12 \rightarrow 11$  emission are peaked at Orion KL very clearly, although it shows prominent star formation already. On the other hand, Figure 4 shows that  $\text{N}_2\text{H}^+$  is rather weak near Orion KL, suggesting that very high temperature due to star formation activity destroys this molecule due to CO evaporation from the dust. The  $\text{HC}_3\text{N}$  linewidth around  $\text{N}_2\text{H}^+$  cores 9 and 10 in OMC-2 is  $\sim 1.2 \text{ km s}^{-1}$  and similar to or only slightly larger than the  $\text{N}_2\text{H}^+$  linewidth.  $\text{HC}_3\text{N}$  seems to be abundant in dense, quiescent gas, even with prominent star formation activities.

We found the displacement between  $\text{N}_2\text{H}^+$  and  $\text{HC}_3\text{N}$  in OMC-3 (Figure 20).  $\text{HC}_3\text{N}$  shows two emission peaks on both sides of  $\text{N}_2\text{H}^+$  core 4.  $\text{N}_2\text{H}^+$  core 4 is associated with two X-ray protostar candidates TKH8 and TKH10 (Tsuboi et al. 2001) (Figure 21). Figure 22 shows  $\text{HC}_3\text{N}$  stamp map (profile map) near TKH8 and TKH10. Tsujimoto et al. (2004)

**Fig. 18.** The antenna temperature of  $\text{N}_2\text{H}^+$  (present study) and CS (Tatematsu et al. 1993) against the declination. The dashed and solid lines connect local maximum intensities in  $\text{N}_2\text{H}^+$  and CS, respectively, to guide the reader’s eye for the global trend.

**Fig. 19.** The  $\text{N}_2\text{H}^+$  distribution with the  $\text{HC}_3\text{N}$  distribution in the OMC-2/3 region. The grey scale represents  $\text{N}_2\text{H}^+$  and contours represent  $\text{HC}_3\text{N}$ . The contour interval is  $0.227 \text{ K km s}^{-1}$ . The grey scale ranges from 0.2 to  $8.0 \text{ K km s}^{-1}$ , while the maximum intensity of the  $\text{N}_2\text{H}^+$  emission is  $9.3 \text{ K km s}^{-1}$ . The crosses represent submillimeter protostars (candidates) by Chini et al. (1997)

**Fig. 20.** The same as Figure 19 but close-up for OMC-3.

concluded that one of the X-ray emitting protostars, TKH8, is a Class I protostar emitting the X-ray emission from the protostellar jet. A possibility is that the displacement represents the chemical evolution. Another possibility is that the degree of molecular depletion varies along the ridge of OMC-3. It is interesting to check whether there is temperature variation. Wilson et al. (1999) shows that CS cores 3, 4, and 5 of Tatematsu et al. (1993) located in OMC-3 have  $\text{NH}_3$  rotation temperature  $T_{\text{rot}} = 15, 19, \text{ and } 20 \text{ K}$ , respectively. CS core 3 is located at R. A. (J2000) =  $5^{\text{h}} 35^{\text{m}} 17^{\text{s}}.6$ , Dec. (J2000) =  $-5^\circ 0' 30''$ , and corresponds to a  $\text{HC}_3\text{N}$  peak on NW side of  $\text{N}_2\text{H}^+$  core 4.  $\text{N}_2\text{H}^+$  cores 4, 5, and 6 have an  $\text{N}_2\text{H}^+$  excitation temperature of  $T_{\text{ex}} = 9.3, 7.5, \text{ and } 6.6 \text{ K}$ , respectively. The dust spectral index is rather constant in the OMC-2/3 region except for MMS6 (Lis et al. 1998; Johnstone & Bally 1999), and the OMC-2/3 region has no dust temperature variation except for MMS6. Because there is no evidence that  $\text{N}_2\text{H}^+$  core 4 has lower temperature in OMC-3, it is not easy to explain the displacement between  $\text{HC}_3\text{N}$  and  $\text{N}_2\text{H}^+$  in terms of different degrees of depletion. Tsujimoto et al. (2004) showed that the Class I X-ray protostar TKH8 has near-infrared  $\text{H}_2$  jets toward the west, although this jet is very small in size. Aso et al. (2000) showed larger-scale CO outflows in this region.  $\text{N}_2\text{H}^+$  is known to trace the quiescent gas, and will be suppressed in outflow affected gas. The displacement between  $\text{HC}_3\text{N}$  and  $\text{N}_2\text{H}^+$  peaks observed in OMC-3 could represent the chemical evolution or the effect of molecular outflow from protostars.

CCS was not detected in the OMC-2/3 region in either transitions. We observed CCS over the same region as  $\text{HC}_3\text{N}$  (Figure 19). We also carried out a strip scan along Dec. (J2000) =  $-5^\circ 58' 07''$ , over the right ascension range R. A. (J2000) =  $5^{\text{h}} 35^{\text{m}} 3^{\text{s}}.8 - 33^{\text{s}}.2$  passing through the southern part of the “f-shaped filament” but have not detected in either transitions of CCS. The  $3\sigma$  upper limit is  $0.10 \text{ K}$  in  $45.4\text{-GHz}$  CCS and  $0.25 \text{ K}$  in  $81.5\text{-GHz}$  CCS. This means that the Orion A cloud is not very young, which is consistent with a scenario that this cloud was being compressed from the north by the Orion superbubble, whose first OB stars formed  $1 - 2 \times 10^7$  yrs ago. (Bally et al. 1987 and references therein). There are other important observations showing the difference between the Orion A cloud and the dark cloud TMC-1. The neutral carbon atom  $\text{C}^0$  and the CO isotopomer show very similar distribution in Orion A and B clouds

**Fig. 21.** The same as Figure 20 but with the positions of X-ray protostars (Tsuboi et al. 2001).

**Fig. 22.** The Stamp map of the HC<sub>3</sub>N profile around the X-ray protostars observed by Tsuboi et al. (2001). Spectra are 4-channel (148 kHz) binned. The X-ray protostars TKH8 and TKH10 are shown (Tsuboi et al. 2001)

(Ikeda et al. 1999; Ikeda et al. 2002). On the other hand, C<sup>0</sup> and the CO isotopomer show quite different distribution in TMC-1. The C<sup>0</sup> cloud is located on the south-east side of the CO cloud containing TMC-1, suggesting a chemical evolution from younger C<sup>0</sup> cloud to CO cloud (Maezawa et al. 1999). This difference will be due to a fact that the Orion A cloud is rather older than TMC-1. The C<sup>0</sup> gas in Taurus represents younger part of interstellar cloud, while Orion clouds are more evolved without having younger cloud. The origin of C<sup>0</sup> in Orion is the photodissociation region inside clumpy molecular clouds penetrated by the UV radiation.

The H<sup>13</sup> CO<sup>+</sup> core AC9 (Aso et al. 2000, R. A. (J2000) = 5<sup>h</sup> 35<sup>m</sup> 20<sup>s</sup>.5, Dec. (J2000) = −5° 5′ 13″) is less prominent in N<sub>2</sub>H<sup>+</sup> and dust continuum. We wonder whether this is a young core. Core AC9 is not prominent in HC<sub>3</sub>N and is not observed in CCS. There is no evidence that this core is young. According to Aso et al. (2000) and Williams et al. (2003), AC9 is located at or near the lobe of the intense outflow from MMS9. We suspect that the H<sup>13</sup> CO<sup>+</sup> enhancement is due to the effect of the intense outflow.

#### 4. Summary

We observed N<sub>2</sub>H<sup>+</sup>, HC<sub>3</sub>N, and CCS in the Orion A cloud. The N<sub>2</sub>H<sup>+</sup> distribution was found to be very similar to that of the dust continuum except for the central part of the Orion Nebula. The N-bearing molecules, N<sub>2</sub>H<sup>+</sup> and NH<sub>3</sub> seem to be more intense in OMC-2, compared with the H<sup>13</sup>CO<sup>+</sup> and CS distribution. This suggests that OMC-2 has higher abundance of N-bearing molecules or higher filling factor of the quiescent gas. We identified 34 molecular cloud cores on the basis of N<sub>2</sub>H<sup>+</sup> data. The N<sub>2</sub>H<sup>+</sup> excitation temperature in the Orion A cloud is 1.6 times as high as that in the Taurus cores. The excitation temperature decreases toward the south, suggesting the core gas density or N<sub>2</sub>H<sup>+</sup> abundance decreases toward the south. The Orion cores have 2.6, 3.2, 4.0 and 32 times larger core size, linewidth, H<sub>2</sub> column density, and core mass than Taurus cores, respectively. The N<sub>2</sub>H<sup>+</sup> linewidth shows variation along the “f-shaped filament.” The N<sub>2</sub>H<sup>+</sup> linewidth is large (1.1–2.1 km s<sup>−1</sup>) over the Orion Nebula region, moderate (0.5–1.3 km s<sup>−1</sup>) in the OMC-2/3 region, and smaller (0.3–1.1 km s<sup>−1</sup>) in the south of Orion Nebula. On the other hand, the gas kinetic temperature of the quiescent cores observed in N<sub>2</sub>H<sup>+</sup> is rather constant (∼ 20 K). The distribution of the HC<sub>3</sub>N emission is globally similar to that of N<sub>2</sub>H<sup>+</sup>. We have not detected CCS anywhere in the OMC-2/3 region. We found a peculiar starless core, AC9, which is intense in H<sup>13</sup>CO<sup>+</sup>, but is not prominent in the dust continuum or N<sub>2</sub>H<sup>+</sup>. The reason of H<sup>13</sup>CO<sup>+</sup> enhancement could be due to the effect of the lobe of the intense protostellar outflow from the adjacent protostar MMS9. We found

a displacement between the  $\text{N}_2\text{H}^+$  and  $\text{HC}_3\text{N}$  distribution in OMC-3, which has a chain of Class 0 and/or Class I protostars (and their candidates), including X-ray emitting protostars. This displacement is likely to represent either the chemical evolution or effect of protostellar outflows.

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Table 1. N<sub>2</sub>H<sup>+</sup> Core Catalog (1)

No.	R.	A.	(J2000)		Dec.	(J2000)	$V_{LSR}$	$R$	$T_A^*$	$T_{ex}$	$\tau_{TOT}$	$\Delta v$	comment
	h	m	s	°	'	"	km s <sup>-1</sup>	"	K	K		km s <sup>-1</sup>	
1	5	35	6.2	-4	54	24	11.13	24	~ 1.3	...	...	0.65±0.05	
2	5	35	6.1	-4	56	7	11.19	43	1.34±0.33	7.5±1.2	3.5±1.4	0.62±0.03	
3	5	35	29.4	-4	58	31	12.32	41	0.84±0.16	5.6±0.5	3.8±1.2	1.31±0.10	
4	5	35	19.8	-5	0	53	11.29	42	2.60±0.11	9.3±0.4	6.6±0.8	0.57±0.01	
5	5	35	26.8	-5	1	13	11.55	29	1.09±0.34	7.5±1.5	2.5±1.1	0.79±0.05	
6	5	35	25.4	-5	2	36	11.13	49	1.57±0.10	6.6±0.3	7.4±1.4	0.51±0.02	
7	5	35	26.7	-5	5	0	11.59	45	2.83±0.13	10.0±0.4	6.2±0.7	0.47±0.01	
8	5	35	32.3	-5	6	2	11.84	24	~ 1.5	...	...	0.74±0.04	
9	5	35	23.9	-5	7	25	11.88	48	1.98±0.29	9.6±1.0	3.4±0.8	0.86±0.04	
10	5	35	26.7	-5	10	9	11.28	47	3.06±0.36	20.3±1.9	1.7±0.2	1.23±0.02	
11	5	35	22.6	-5	10	9	11.67	26	2.41±0.43	12.4±1.8	2.7±0.7	0.62±0.02	
12	5	35	22.7	-5	12	32	10.97	51	4.00±0.34	18.6±1.3	2.7±0.3	0.93±0.02	
13	5	35	21.2	-5	14	36	10.82	46	2.31±0.21	9.1±0.7	4.4±0.8	0.62±0.02	
14	5	35	8.8	-5	18	41	9.00	41	1.47±0.30	7.9±1.1	3.5±1.2	0.62±0.03	
15	5	35	15.8	-5	19	26	9.94	55	3.51±0.15	16.4±0.5	2.8±0.2	1.31±0.02	
16	5	35	8.9	-5	20	22	8.63	52	~ 1.2	...	...	2.05±0.09	
17	5	35	10.3	-5	21	25	8.11	36	~ 1.7	...	...	1.08±0.05	
18	5	35	6.1	-5	22	46	7.45	28	~ 0.7	...	...	2.06±0.14	
19	5	35	12.9	-5	24	10	6.58	36	~ 1.0	...	...	2.12±0.07	
20	5	35	4.7	-5	24	13	8.58	21	~ 0.8	...	...	1.92±0.10	
21	5	35	15.7	-5	25	54	8.23	30	1.32±0.42	10.8±2.4	1.6±0.6	1.15±0.06	
22	5	35	14.3	-5	26	56	8.79	36	~ 0.9	...	...	1.72±0.07	skew
23	5	35	2.0	-5	36	10	7.27	57	1.52±0.03	6.1±0.2	11.6±1.6	0.32±0.01	
24	5	35	4.8	-5	37	32	8.79	41	1.75±0.13	7.3±0.4	6.2±1.2	0.72±0.03	double pe
25	5	34	56.6	-5	41	39	3.66	42	0.79±0.14	...	...	0.48±0.03	
26	5	34	57.7	-5	43	41	7.15	30	1.13±1.02	9.8±6.5	1.5±1.7	0.41±0.03	
27	5	34	56.3	-5	46	5	5.52	36	0.68±0.16	5.4±0.6	3.1±1.1	1.11±0.08	
28	5	35	8.8	-5	51	57	6.99	40	~ 1.1	...	...	0.38±0.05	
29	5	35	0.7	-5	55	40	8.03	30	0.89±0.46	6.1±1.9	3.2±2.5	0.49±0.05	
30	5	35	9.0	-5	55	41	7.47	26	1.39±0.57	9.2±2.7	2.3±1.3	0.64±0.04	
31	5	35	12.8	-5	58	6	7.62	41	0.67±0.62	...	...	0.83±0.09	
32	5	35	28.1	-6	0	9	7.29	78	0.57±0.08	4.2±0.4	8.2±4.2	0.35±0.04	
33	5	36	12.4	-6	10	44	8.16	28	0.70±0.14	4.7±0.5	5.6±2.5	0.62±0.06	
34	5	36	24.7	-6	14	11	8.19	36	~ 0.5	...	...	0.92±0.16	



**Table 1.** (Continued.)

ave	$39 \pm 12$	$1.49 \pm 0.87$	$9.2 \pm 4.2$	$4.3 \pm 2.5$	$0.92 \pm 0.52$
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**Table 2.** N<sub>2</sub>H<sup>+</sup> Core Catalog (2)

No.	$R$	$N(\text{N}_2\text{H}^+)$	$N(\text{H}_2)$	$n(\text{H}_2)$	$M$	Paper I	Aso	Object
	pc	cm <sup>-2</sup>	cm <sup>-2</sup>	cm <sup>-3</sup>	$M_\odot$			
1	0.053	...	...	...	...			
2	0.094	1.3E+13	4.2E+22	7.3E+04	25.9			
3	0.089	2.5E+13	8.2E+22	1.5E+05	44.6	2		CSO3
4	0.091	2.6E+13	8.8E+22	1.6E+05	50.0	3	3	H,MMS2-4,CSO5-6,VL
5	0.064	1.2E+13	4.0E+22	1.0E+05	11.2	4	5	
6	0.107	2.1E+13	6.9E+22	1.0E+05	54.4	5	7,8	H,MMS7
7	0.098	2.2E+13	7.3E+22	1.2E+05	48.0	6	10	H,MMS8-9
8	0.053	...	...	...	...	7	12	O,MMS10
9	0.106	2.1E+13	7.1E+22	1.1E+05	54.6	8	14	O,OMC-2 FIR1a-c
10	0.102	2.8E+13	9.2E+22	1.5E+05	66.2	11	17	OMC-2 FIR4
11	0.056	1.5E+13	5.0E+22	1.4E+05	10.7		16	
12	0.111	3.1E+13	1.0E+23	1.5E+05	89.5	13		
13	0.101	1.9E+13	6.4E+22	1.0E+05	44.9	16		
14	0.089	1.4E+13	4.5E+22	8.2E+04	24.5	19		
15	0.120	4.1E+13	1.4E+23	1.9E+05	135.9	21		
16	0.113	...	...	...	...			
17	0.080	...	...	...	...			
18	0.061	...	...	...	...			
19	0.078	...	...	...	...	31		Ori-S
20	0.047	...	...	...	...	33		
21	0.066	1.4E+13	4.8E+22	1.2E+05	14.6	36		
22	0.080	...	...	...	...	37		
23	0.124	2.0E+13	6.5E+22	8.5E+04	68.6	46		
24	0.089	2.6E+13	8.8E+22	1.6E+05	47.8	47		
25	0.091	...	...	...	...			
26	0.066	...	...	...	...	51		
27	0.080	1.6E+13	5.4E+22	1.1E+05	23.7	51		
28	0.087	...	...	...	...	54		
29	0.066	...	...	...	...			
30	0.056	1.0E+13	3.4E+22	9.7E+04	7.3	56		
31	0.089	...	...	...	...	57		
32	0.170	1.2E+13	4.0E+22	3.8E+04	78.0			
33	0.061	1.5E+13	5.1E+22	1.3E+05	13.1	61		
34	0.078	...	...	...	...	64		

**Table 2.** (Continued.)

ave	$0.086 \pm 0.025$	$2.0 \pm 0.8 \times 10^{13}$	$6.7 \pm 2.6 \times 10^{22}$	$1.2 \pm 0.4 \times 10^5$	$45.7 \pm 32.0$
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